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Overtopping Measurements on the Wave Dragon Nissum Bredning Prototype.

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ABSTRACT

The paper describes the methods used to estimate (calculated from some indirect measurements) the overtopping of the wave energy converter Wave Dragon placed in a real sea environment. The wave energy converter in quistion is the 237-tonne heavy Wave Dragon Nissum Bredning Prototype. Comparisons are made with laboratory measurements of the overtopping of a laboratory-scale model.
KEY WORDS: Wave Energy; Overtopping; Prototype Testing; Wave Dragon; Low-Pressure Turbine; Scale Effects;

INTRODUCTION

Figure 1: The Wave Dragon Nissum Bredning Prototype.

The Wave Dragon is an offshore wave energy converter of the overtopping type. 4-11 MW if placed in the North Sea. For the Nissum Bredning 18.2 kW is installed.

Basically it consists of two floating wave reflectors focusing the waves towards a ramp, a floating reservoir for collecting the overtopping water, and some hydroturbines for converting the pressure head into power.

Figure 2: Location of the Nissum Bredning Prototype

Over the period 1998 to 2001, extensive testing on a scale 1:50 model was carried out at Aalborg University. During recent months, testing has started on a prototype of the Wave Dragon in Nissum Bredning, Denmark (scale 1:4.5 off the North Sea).

Figure 2 shows the location of the Nissum Bredning Prototype, indicated on the map by the ellipse. The Nissum Broads (Nissum Bredning) are just off the North Sea, separated from it by two tongues of land.

Figure 3 shows the average wave energy density in the Broads. The upper arrow on the figure indicates the present location of the Nissum Bredning Prototype; the lower arrow shows the most exposed location in the Broads, to which the machine will be moved during early summer 2004.

The present location was chosen to test the functionality of the machine, as easier access to the machine makes it possible to sort out the inevitable 'teething troubles' before deploying it in the most exposed position.

The Nissum Bredning Prototype was grid connected at its first location (upper arrow on figure 3), thus making it the world's first offshore wave energy converter.

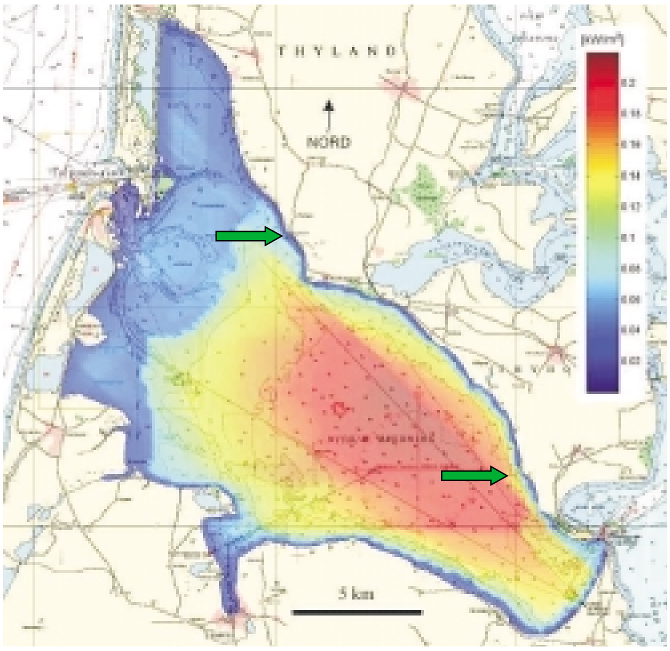

Figure 3: Energy density in Nissum Bredning. The figure also shows the 2 different locations where the machine will be placed.

The Wave Dragon Nissum Bredning Prototype has a total weight of 237 tonnes, still it is only a scale 1:4.5 of the eventual North Sea Prototype.

Over the next 2 years, an extensive measuring program will establish the background for optimal design of the structure and regulation of the power take-off system. Planning for a full scale deployment within the next 2-3 years is in progress (Sørensen et. al. 2003). Such a structure will probably be placed somewhere in the North Sea, or in the North Atlantic Ocean.

The Nissum Bredning Prototype is instrumented to monitor power production, wave climate, forces in mooring lines, stresses in the structure, and movements of the Wave Dragon reservoir and the reflecting arms.

The present paper compares the estimated overtopping rates (calculated from indirect measurements) of the Nissum Bredning Prototype with overtopping rates measured in a hydraulic laboratory using a scale 1:50 model (scale 1:11.1 relative to the Nissum Bredning Prototype).

THE WAVE DRAGON CONCEPT

The Wave Dragon consists of three main elements:

- Two wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially, and thereby increase the energy captured by approx. 100% under typical wave conditions.
- The main structure consisting of a doubly curved ramp and a reservoir.
- A set of low head Kaplan-propeller turbines for converting the hydraulic head in the reservoir into electricity.

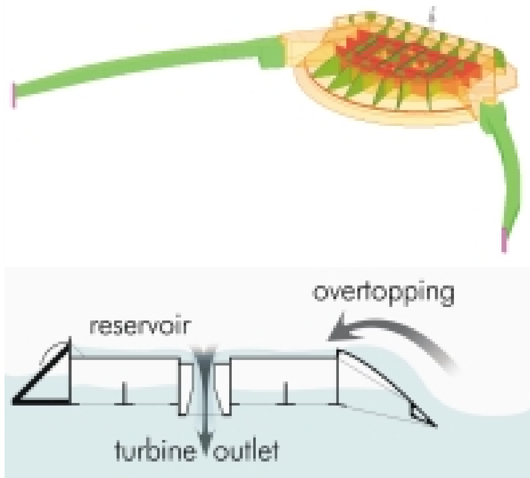

Figure 4: The Basic principle of the Wave Dragon.

When the waves overtop the ramp, this water is filled into the floating reservoir at a higher level than the surrounding sea, and this hydraulic head is utilized for power production through the specially designed hydroturbines.

Through an advanced phenumatic system it is possible to adjust the floating level. The entire main body of the Wave Dragon can be raised or lowered, and in this way the crest freeboard can be varied in order to maximize energy output from the Wave Dragon under the sea conditions prevailing at any time. This level adjustment happens continuously. The used time scale for the operation corresponds to approx. 250 wave periods.

Knowledge about overtopping rates is privotal for establishing the optimal regulation strategy for the Wave Dragon and for the efficiency achievable from the Wave Dragon. What is the optimal floating level for a given sea condition? When is the optimal time to switch on or switch off the turbines?

Equations predicting average overtopping rates for the Wave Dragon were first established through tank tests at Aalborg University on a scale 1:50 model in 1998-1999 (Martinelli and Frigaard 1999).

Martinelli and Frigaard 1999 tested the Wave Dragon in long-crested seas as well as in short-crested seas with some standard JONSWAP spectra. They presented the following equation to predict overtopping (linear ramp inclination 45 deg.):

$$q = 0.017c_d \cdot exp(-48\frac{R_c}{H_s}\sqrt{\frac{S_{op}}{2\pi}})\frac{L\sqrt{gH_s^3}}{\sqrt{\frac{S_{op}}{2\pi}}}$$

where,

q	=	discharge due to overtopping
c_d	=	reduction coefficient accounting for directional spreading effects, c_d = 0.9
L	=	length of structure ramp; a length of 86.6 meter was assumed (21.3 meter for the Nissum Bredning Prototype)
S_{op}	=	$H_s/L_{op}, where L_{op} = \frac{g}{2\pi}T_p^2$
T_p	=	peak period; a constant ratio 1.2 between the peak and the mean period was assumed
H_s	=	significant wave height
R_c	=	crest freeboard

The Wave Dragon model tested by Martinelli and Frigaard 1999 turned out to have some rather large movements; consequently the dynamic behaviour of the model was slightly changed.

Kofoed 2003 tested various slope layouts in order to find a structure producing the maximum overtopping effect. Kofoed's tests verified a doubly curved ramp to have a significantly positive effect.

Incorporating these changes, a second-generation model was constructed and tested at Aalborg University in 2001. A photo of the model and the prototype can be seen in figure 5.

Figure 5: Photo showing the doubly curved ramp.

Hald and Frigaard 2001 reported overtopping from the tests with the second-generation model, and presented a modified overtopping equation:

$$q = 0.025c_d \cdot exp(-40\frac{R_c}{H_s}\sqrt{\frac{S_{op}}{2\pi}})\frac{L\sqrt{gH_s^3}}{\sqrt{\frac{S_{op}}{2\pi}}}$$

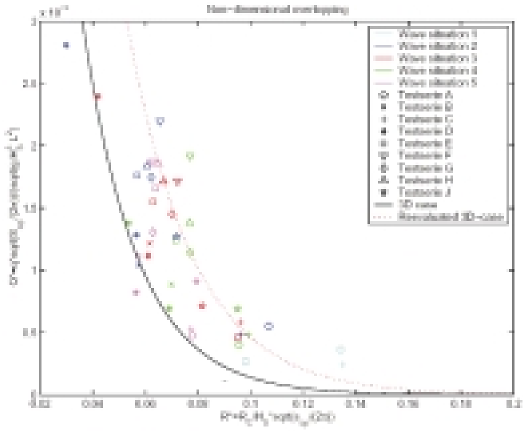

Figure 6: Dimensionless overtopping relation.

Figure 6 shows the test data from Hald and Frigaard 2001. Tests first carried out using the original model layout in Martinelli and Frigaard 1999 were repeated by Hald and Frigaard 2001; these tests are labelled Test series A and Test series B in the figure. A reasonable fit with the Martinelli and Frigaard 1999 equation (full line) is seen. Test series C and D represent minor modifications made to the reflector draught; resulting in a small increase in the overtopping. Test series E to J represent data measured on the model with the doubly curved overtopping ramp implemented. The effect of the doubly curved ramp is clearly seen. The Hald and Frigaard equation (dotted line) is also shown on the figure together with the original data points.

All data shown in figure 6 represent 5 standard wave conditions. Each data point corresponds to a test including approx. 1000 waves in a controlled wave environment. In table 1 the wave conditions are listed in North Sea scale. The reason for choosing the Nissum Broads location for the 1:4.5 scale model of the Wave Dragon was indeed the fact that the wave climate in Nissum Broads corresponds very well with the wave climate in the North Sea, scaled by 4.5.

Situation	H_s	T_p	Frequency	Energy
[-]	m	sec.	% of time	MWhmyear
1	1.0	5.6	46.7	8.2
2	2.0	7.0	22.6	23.8
3	3.0	8.4	10.8	30.2
4	4.0	9.8	5.1	29.4
5	5.0	11.2	2.4	24.3

Tabel 1: Tested wave situations.

In addition, an overtopping simulation software tool had to be developed, allowing real time simulations of overtopping rates

(Jacobsen and Frigaard 1999). The design of the reservoir and the turbine configuration of the Wave Dragon had to be based on a reasonable input discharge history. The time history was considered a random process, and it was generated according to a distribution of overtopping volumes per wave consolidated in literature and mean values obtained by the tests previously described.

The probability of occurrence of wave overtopping for vertical structures, cf. Franco et al. 1994 and for rubble mound dikes, cf. van der Meer and Janssen 1995, can be given in the form of a Rayleigh type distribution:

$$P_{ov} = exp(-(\frac{R_c}{cH_s})^2)$$

where,

c	=	a constant; set to 1.21 c can be interpreted as a roughness factor.

According to van der Meer and Janssen 1995, the distribution of the overtopping volumes of the individual waves, given that overtopping takes place, is given by a Weibull distribution with shape parameter 0.75:

$$P_{V|ov} = P(V \leq V_{mean}|o) = 1 - exp(-(\frac{V_{mean}}{a})^{0.75})$$

where,

a	=	$\frac{qT_m}{P_{ov}}$
q	=	mean overtopping discharge
T_m	=	mean wave period; a constant ratio 1.2 between the peak and the mean period was assumed.
P_{ov}	=	the probability of overtopping given in the equation above
$V_{mean}\|o$	=	mean overtopping of wave, given wave is overtopping

Note that the scale factor a used for the quantification of the overtopping, given that overtopping takes place, is the average overtopped volume, magnified due to the 'average' overtopping probability.

The probability P_v, that a generic wave (the comming wave) is associated to a overtopping volume V less or equal to V_{mean} is:

$$P_v = P(V \leq V_{mean}) = P_{V|ov} \cdot P_{ov}$$

Kofoed and Burchart (2000) verified the equations giving the time variations of the overtopping for smooth slopes

TURBINE CONFIGURATION

In order to maximize energy output from the Wave Dragon, the machine is equipped with several small turbines rather than one larger turbine. In this way it is possible e.g. to switch on only a part of the installed power in sea conditions producing relatively small amounts of overtopping water. Furthermore this construction allows a single small turbine to be switched on or switched off depending on the actual amount of water coming from a single wave.

The regulation strategy for the Wave Dragon consists of 2 steps. First, the optimal crest freeboard (float level) for the actual sea condition is calculated. For this calculation a time scale corresponding to approx. 250 wave periods is used. Second, the 'work span' for the turbines needs to be defined. The 'work span' is defined as the the accepted variation in the water level in the reservoir. Once the water level reaches the top of the 'work span' in question, all turbines will be switched on. And correspondingly, when the water level reaches the lowest level of the 'work span' all turbines will be switched off.

Figure 7: Kaplan turbine with cylinder gate.

A number of different strategies to control this mechanism will be tested in the coming years in order to maximize energy output. For the time being, the 'work span' is simply divided into a number of distances.

Ideally, the Wave Dragon would be equipped with several similar small turbines; however, the actual turbine configuration is a result of compromises brought on by financial constraints rather than logical, optimal technical solutions. Like most other wave energy projects, the Wave Dragon project had to adjust the turbine configuration according to the available funds. Therefore, the Wave Dragon is equipped with 3 different types of turbines:

- A Kaplan turbine with Siphon inlet, see figure 9. The turbine was developed through the EU CRAFT project: Low–Pressure Turbine and Control Equipment for Wave Energy Converters (Wave Dragon). Diameter of the Siphon turbine is 0.34 meter, and area of cross section is 0.0908 m^2. Rated power output is 2.6 kW (500 kW for the North Sea Wave Dragon). Calibrated flow is 0.22 $M^3/sec.$ at 0.5 meter head.
- 3 Dummy turbines, see figure 8. The turbines are not able to produce power, but simply let the overtopped water run back into the sea through a set of calibrated valves. Diameter of the valves are 0.43 meter, and area A of cross section is 0.147 m^2. The discharge Q through the dummy turbines was calibrated to follow the equation $Q = k \cdot A\sqrt{2gh}$, (h=pressure head). For the 3 dummy turbines the k-values were found to be 1.05, 1.07 and 1.09 (Knapp and Riemann 2003).
- 6 Kaplan turbines with cylinder gates, see figure 7. These turbines have data similar to the 'Siphon' Kaplan turbine. Diameter of these turbines is 0.34 meter. Rated power output is 2.6 kWatt. Calibrated flow 0.22 m^3/sec at a head of 0.5 meter. The turbines were fabricated in Austria by Kössler, and were installed in September 2003. Installation of gear and generators were finished February 2004.

Figure 8: The 3 'dummy' turbines.

Based on measurements of the instantaneous pressure head, and knowing the number of currently open turbines, it is possible to calculate the flow through the turbines. The opening period is defined as the period from starting time of the opening process to starting time of the closing process. Obviously the periods of the opening and closing operations will be accompanied by

Figure 9: Kaplan turbine with Siphon inlet

some uncertainty. In particular, it must be stressed that the actual amount of water passing the turbines will be slightly lower than calculated, as the flow through the turbines is not linearly depending on the head. However, relative to the typical duration of the operations of the turbines (open valves), the duration of the opening of and closing processes of the valves are insubstantial.

WAVE MEASUREMENTS IN NISSUM BREDNING

Waves are measured indirectly through a pressure transducer placed approx. 2 meter under the sea surface. The pressure transducer is mounted on an arm attached to the mooring pile of the Wave Dragon. The transformation from pressure to surface is done by linear wave theory.

Wave parameters are calculated continuously in a 17 minutes long time window. The length of the time window corresponds to 250 - 300 waves. Zero down crossing analyses are performed and the average period T_m is used to characterize the waves. The peak periods T_p of the spectra are assumed to be $T_p = 1.2 \cdot T_m$.

PROTOTYPE OVERTOPPING

The Wave Dragon floats on air chambers to make it possible to adjust the floating level of the machine. Therefore, scale effects have to be considered, and tank tests are not directly scalable. Scale effects will mainly be presented on the movements of the Wave Dragon, and laboratory tests have shown that the overtopping is very strongly depending on the movements. It must be mentioned that movements have been measured in all laboratory tests, and that the Nissum Bredning Prototype is equipped with 6 accelerometers in order to measure movements. Analyses of the movements have still to be performed.

During the winter of 2003/2004 and over the coming winter, overtopping results have been and will be collected continuously, in periods without down time of the instruments.

Obtaining measurements in a real sea condition is difficult. And it has indeed turned out to be even more difficult and time-consuming than expected. The sea is extremely rough on the instruments. Nevertheless, throughout the months of November and December 2003 average overtopping rates have been successfully monitored on the Nissum Bredning Prototype, both under ordinary conditions and under storm conditions (Kofoed and O'Donovan 2003).

It is assumed that all water overtopping the ramp passes through the turbines. This means that no spill is expected. Visual inspections support this assumption; at least in calmer wave conditions.

Therefore, an estimate of the overtopping amount can be calculated, knowing the characteristics of the turbines, the head of the free surface and the opening time of the turbines.

Figure 10 gives an example of the measurements. Unfortunately,it is difficult to see the measurements clearly in the figure; however, the purpose of including the plot is to give an idea of the variations in the signals.

The x-axis represents the time. The length of the axis is 5 minutes corresponding to a little less than 100 waves.

The y-axis shows 5 curves: 'work span' (in this example app. 10 cm), water level within 'work span' (in this example 0% - 100%), number of running turbines (0-10 in the example), wave height (approx 50 cm in the example) and water level in reservoir (50-60 cm in the example).

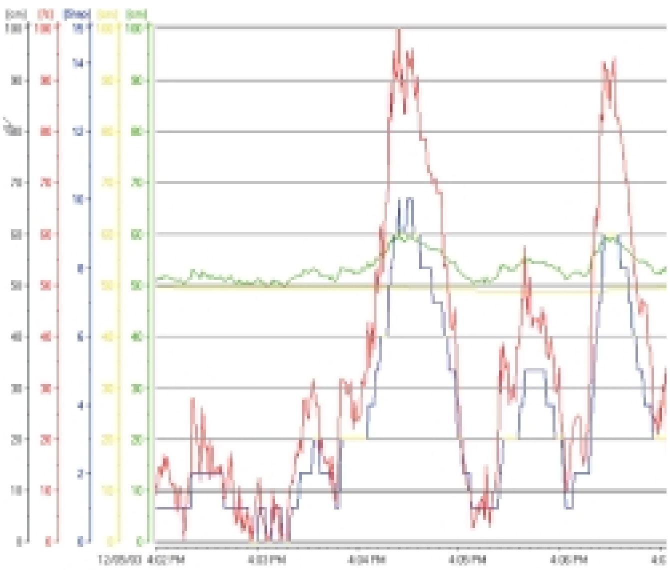

Figure 10: Measured data as shown in the control program.

From figure 10 each individual wave can be recognized as a change in the water level in the reservoir. This can be seen most clearly when studying the curve for the water level within the 'work span' (red curve).

Figure 10 also demonstrates the frequency for the turbines to be switched on (and later switched off). The situation seen on the figure corresponds to a turbine being switched on almost every 10 second in average.

The outlet is calculated as:

$$Q_{overtop} \simeq Q_{out} = \int_{time} \sum_{i=1}^{N} F_i(h) G_i dt$$

where,

i	=	turbine number
N	=	number of installed turbines
h	=	instantaneous head in reservoir
F	=	calibrated function describing flow out through a turbine
G	=	function describing whether the turbine valve is opened or closed. At present this function can only take the values 0 or 1.

The overtopping data from the Nissum Bredning Prototype show good agreement with the laboratory overtopping data, although slightly more overtopping is seen on the Nissum Bredning Prototype than expected from the laboratory.

Figure 11 gives an example of such a comparison.

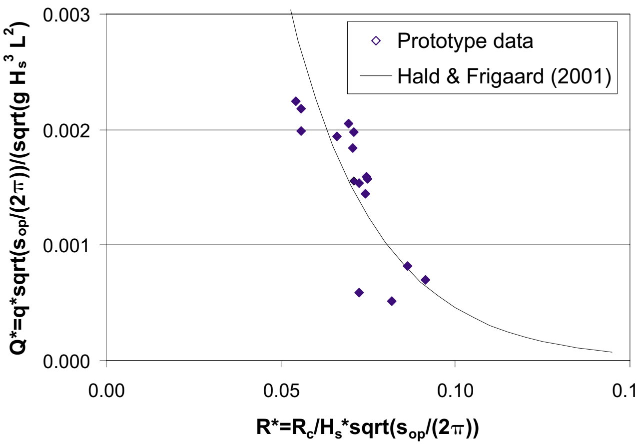

Figure 11: Example of Overtopping results

In the near future, much more data covering a larger parameter range can be expected. Hopefully, this will lead to more detailed conclusions. For the time being, however, we find it surprising, that the data do in fact correspond so well. Normally, overtopping data show an enormous scatter, even for laboratory data. A factor of 5-10 is not unusual in literature. However, for the conditions with large amounts of overtopping less scatter is normally seen.

In the controlled laboratory environment, the waves were generated, Rayleigh distributed, with a standard JONSWAP spectrum and a standard groupiness factor. The sea conditions were kept constant for a period corresponding to 1000 waves. In the real sea in Nissum Broads, the wave conditions are much more scattered.

It seems like, very few scale effects can be observed. The Wave Dragon floats on an air cushion, which means that in order to establish a correct model, the stiffness of this air cushion has had to be scaled. Such a scaling is very difficult to implement correctly, and a certain amount of scale effects was to be expected.

Measurements of the movements of the Nissum Bredning Prototype have not been analysed yet, but based on several visits and a preliminary look at the data, we think that some scale effects are present on the movements (larger movements in laboratory).

CONCLUSION

Overtopping has been measured on the Nissum Bredning Prototype of the Wave Dragon. The functionality of the Wave Dragon overtopping concept has been proven.

Good agreement to laboratory-based overtopping equations was found, although some more overtopping was measured in the Nissum Bredning Prototype.

The extra overtopping is assumed to originate from wind effects, and from scale effects on the movements of the Wave Dragon.

ACKNOWLEDGEMENTS

The Wave Dragon has recieved support from The European Commission, The Danish Energy Agency and several private companies and foundations. Please see homepage for a full list.

MORE INFORMATION

Futher information on the project can be found at one of the Web pages: www.wavedragon.net or www.civil.aau.dk for further information on the project.

REFERENCES

Franco, L., Gerlone, M.D. and Van der Meer, J.W. (1994): Wave overtopping at vertical and composite breakwaters. Proc 24th International Conference on Coastal Engineering, Kobe, Japan. ASCE.

Hald, Tue and Frigaard, Peter (2001): Forces and Overtopping on 2. generation Wave Dragon for Nissum Bredning. Phase 3 project, Danish Energy Agency. Project no: ENS-51191/00-0067. Hydraulics & Coastal Engineering Laboratory, Aalborg University.

Jacobsen, K.P. and Frigaard, P. (1999): User's manual for the Program Wave Dragon – Power Simulation. Aalborg University.

Knapp, W. and Riemann, S. (2003): Measurements on Wave Dragon, Nissum Bredning on 24th of May 2003: Dummy turbine calibration. Laboratorium für Hydraulische Maschinen, Technische Universität München.

Kofoed J. P. and Burcharth H. F. (2000): Experimental verification of an empirical model for time variation of overtopping discharge. 4. European Wave Energy Conference (EWEC 2000), Aalborg, Denmark, Dec. 2000.

Kofoed J. P., Frigaard P., H. C. Sørensen and E. Friis-Madsen (2000): Development of the Wave Energy Converter - Wave Dragon. ISOPE-2000, Seattle, USA, May, 2000.

Kofoed J. P.(2003): Wave Overtopping of Marine Structures - Utilization of Wave Energy. Ph. D. Thesis, defended January 17, 2003 at Aalborg University. Department of Civil Engineering.

Kofoed, J. P. and O'Donovan, E. (2003): Status report - First offshore experiences, Wave Dragon, Nissum bredning. Hydraulics & Coastal Engineering Laboratory, Aalborg University, September 2003. (Confidential).

Martinelli, L. and Frigaard, P. (1999): The Wave Dragon: 3D overtopping tests on a floating model. Low-Pressure Turbine and Control Equipment for Wave Energy Converters (Wave Dragon), contract JOR3-CT98-7027. Aalborg University.

H.C. Sørensen, E. Friis-Madsen, W. Panhauser, D. Dunce, J. Nedkvinte, P. Frigaard, J.P. Kofoed, W. Knapp, S. Riemann, E. Holmen, A. Raulund, J. Præst, L.K. Hansen, L. Christensen, T. Nöhrlind, T. Bree, P. McCullen (2003): Development of Wave Dragon from Scale 1:50 to Prototype. Proc. 5th European Wave Energy Conference, Cork Ireland.

Van der Meer, J.W. and Janssen, J. P. F. M. (1995): Wave Run Up and Wave Overtopping at Dikes. Task Committee Reports, ASCE.